Project title: ENHANCEMENT AND DEVELOPMENT OF NUMERICAL MODELS FOR SIMULATING COASTAL SEDIMENT TRANSPORT AND MORPHOLOGY EVOLUTION

Principal Investigator: Dr. Hans Hanson

Contractor: Dept. of Water Resources Engineering
Institute of Technology, U. of Lund
Box 118, Lund, Sweden S-221 00

Contract No: N62558-07-C-0003

Interim Report 3

October 2007 – June, 2008

The research reported in this document has been made possible through the support and sponsorship of the U.S. Government through its European Research Office of the U.S. Army. This copy is intended only for the internal management use of the Contractor and the U.S. Government.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**
4. TITLE AND SUBTITLE **Enhancement and Development of Numerical Models for Simulating Coastal Sediment Transport and Morphology Evolution**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Water Resources Engineering,Institute of Technology, U. of Lund,Box 118,Lund, Sweden S-221 00,**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**18**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

ENHANCEMENT AND DEVELOPMENT OF NUMERICAL MODELS FOR SIMULATING COASTAL SEDIMENT TRANSPORT AND MORPHOLOGY EVOLUTION

I. SCIENTIFIC WORK ACCOMPLISHED

1. Introduction

1.1 Background

During severe storms high waves and water levels may greatly impact the subaerial portion of the beach inducing significant morphological change at elevations where the waves can not reach under normal conditions. Coastal dunes may suffer direct wave impact and erode, increasing the likelihood of breaching and subsequent flooding of low-lying areas behind the dunes. Overwash occurs if the wave runup and/or the mean water level are sufficiently high allowing for water and sediment to pass the beach crest, which in turn causes flooding and deposition of sediment shoreward of the crest (Donnelly *et al.* 2006). In the case of overwash, severe lowering of the crest may take place, increasing the probability of flooding and breaching as the natural defense offered by the subaerial morphological features (e.g., dunes) is weakened.

A barrier island is another type of morphological feature that is vulnerable to high waves and water levels. Typically, these features are regularly exposed to overwash because the crest tends to be at a low elevation. The shoreward transport of sediment in connection with overwash is an important element in the sediment budget for a barrier island and this transport is also thought by many researchers to be the cause of the onshore migration that many such islands are experiencing (Fisher and Stauble 1977, Leatherman 1979). Because the crest of a barrier island is typically low-lying, the mean water level during a storm might exceed the crest elevation leading to inundation overwash. The case when the mean water level is below the crest but the runup passes over it is often denoted as runup overwash. Other morphological features such as spits, or shore-attached shoals that perch the water surface, may exhibit frequent overwash and display similarities to barrier islands in terms of the response, albeit at a smaller scale.

Coastal engineers are often faced with estimating the impact on the beach of severe storms in terms of, for example, eroded volume, recession distance, and overwash volumes. Several numerical models have been developed for this purpose (Kriebel and Dean 1985, Larson and Kraus 1989, and Steetzel 1993), but they are in general time-consuming to apply and require a significant amount of data at a high level of detail. Furthermore, only a limited number of models include the possibility to simulate overwash (Larson *et al*. 2004a, Donnelly *et al.* 2007). As an alternative to a numerical approach an analytical model might be employed, requiring limited input data. The use of an analytical model involves a high degree of schematisation concerning the forcing, boundary, and initial conditions, but if the model captures the main governing physics, reliable estimates of storm impact on beaches are obtained that could be used in preliminary studies. Another application for analytical models is

to derive long-term statistical properties of key parameters quantifying morphological impact of storms. Long time series of wave and water level data, together with beach profile and sediment characteristics, may serve as input for computing time series of such parameters (e.g., eroded volume, recession distance, and overwash volume). Subsequently, different types of statistical analysis can be used to estimate the probability of a certain morphological impact on the beach in connection with a storm. This is an important step in a risk-based strategy to manage coastal erosion and flooding.

1.2 Objectives

The main objectives of the research reported here were: (1) to develop an analytical model of erosion due to wave impact and sediment transport in the overwash; (2) to validate the model with high-quality field data; and (3) to develop methods to employ the model for estimating the statistical properties of morphological response in connection with storms based on long time series of input data on waves and water level.

1.3 Procedure

The transport formula developed by Larson *et al*. (2004b) was employed to compute dune or barrier island erosion due to wave impact. The eroded sediment is transported offshore or over the beach crest (overwash) depending on the wave and water level conditions in relation to the crest elevation. A simple analytical model was derived for a triangular subaerial cross section, which is often a good characterization of dunes and barrier islands. The model includes three variables to describe the beach response, namely the crest height, the seaward (front) beach foot location, and the shoreward (rear) beach foot location. Three sand conservation equations govern the beach response.

A high-quality database on subaerial profile response due to wave impact and overwash in the field was compiled to validate the employed transport formulas and the analytical solutions to describe beach evolution. The field data included pre- and post-storm profiles and the associated wave and water level forcing, as well as sediment characteristics, for several major storm events. Also, long-term time series of wave and water level data encompassing 70 years at a resolution of 1 hr, originating from Ocean City (MD), were employed to calculate dune erosion and overwash transport for statistical analysis. The long-term wave and water level data were used as input to the analytical model to calculate time series of morphological impact parameters, primarily eroded volume, overwash volume, and recession distance. Empirical distribution functions were derived from these times series as a basis for assessing the probability of exceedance for a specific event.

2. Analytical model of beach response

2.1 Wave impact

Larson *et al.* (2004b) developed a sediment transport formula for the erosion from a dune face due to wave impact based on work by Fisher *et al*. (1986; see also Overton *et al*., 1987, and Nishi and Kraus, 1996). This model was combined with the sediment continuity equation and then solved analytically for simple cases with regard to geometry and forcing. The basic assumption in estimating dune erosion from wave impact theory is that there is a linear relationship between the impact (force, *F*, on the dune due to change in the momentum flux of the bores impacting the dune) and the

weight, ΔW, of the sediment volume eroded from the dune according to $\Delta W = C_E F$, where C_E is an empirical coefficient (see Fig. 1 for a definition sketch). The weight of the eroded volume ΔV is given by $\Delta W = \Delta V \rho_s (1-p) g$, where ρ_s is the density of the sediment, p sediment porosity, and g acceleration due to gravity. The swash force, F, is a result of the change in the momentum of the bores hitting the dune and it may be estimated from $F \sim \rho u_o^2 h_o \Delta t / T$, where ρ is the water density, u_o the speed of the bore, h_o the height of the bore, $\Delta t/T$ the number of incoming waves during the period Δt, and T the period at which waves hit the dune (taken to be approximately equal to the incident wave period).

Equating swash force and weight of eroded volume, and considering the process of dune erosion to be continuous, although in reality it is often discrete depending on the prevailing failure mechanism (Erikson *et al*. 2003, 2007), an average rate of dune erosion, q_D, is derived,

$$q_D = \frac{dV}{dt} = -C_s \frac{u_o^4}{g^2 T} \tag{1}$$

where C_s is an empirical transport coefficient and a minus sign was introduced since the dune volume must decrease with time (t). In order to arrive at Eq. 1 it was assumed that the speed of the bore is related to the bore height according to $u_o \sim \sqrt{g h_o}$ (e.g., Cross, 1967; Miller, 1968). The bore speed in front of the dune face, u_o, is estimated as, $u_o^2 = u_s^2 - 2 g z_o$, where u_s is the velocity of the bore as it starts its travel up the foreshore and z_o the elevation difference between the dune foot and the beginning of the swash (see Fig. 1). This estimate of u_o is obtained by regarding the bore as a slug of water moving along the foreshore (friction neglected; e.g., Waddell, 1973; Hughes, 1992). At the limit of the runup, R, the velocity u_o should be zero, implying that $u_s^2 = 2gR$, which means that predictive formulas for R may be used to derive u_s. By substituting in the expression for u_o in Eq. 1, using R instead of u_s, the following equation is obtained for the dune response:

$$\frac{dV}{dt} = -4C_s \frac{\left(R - z_o\right)^2}{T} \tag{2}$$

For the case when R and z_o are constants, the following solution to Eq. 2 is obtained,

$$V = V_o - 4C_s \left(R - z_o\right)^2 \frac{t}{T} \tag{3}$$

where the initial condition $V = V_o$ at $t = 0$ was employed. Thus, the eroded volume $\Delta V_E = V_o - V$ after time t may be determined to be $\Delta V_E = 4C_s \left(R - z_o\right)^2 t / T$.

2.2 Overwash

Coastal overwash is the flow of water and sediment over the crest of the beach (e.g., dune or barrier island) that does not directly return to the ocean from where it originated (Donnelly *et al.* 2006). Only a few formulas have been developed to

estimate sediment transport by overwash and they are typically based on the flow of water over the crest (Kraus and Wise, 1993; Kobayashi *et al.*, 1996; Larson *et al.*, 2004). In more sophisticated formulations different approaches are employed depending on the type of overwash regime, that is, whether runup or inundation overwash occurs (Donnelly *et al*., 2007). In most cases runup overwash occurs before and after inundation overwash during a specific event, implying that a fine resolution in time is needed to model the processes in detail. Thus, such modeling requires a numerical approach, whereas in an analytical description considerable simplifications are employed to arrive at closed-form solutions. These simplifications would involve schematised geometries, constant or representative forcing (waves and water level), and a limited number of parameters to describe the evolution of the beach in response to overwash. In the following, a simple analytical model to simulate the effect of overwash and erosion of the seaward side of the beach (the source of the overwash deposits) on the subaerial profile shape is developed.

2.3 Analytical solution

Dune and barrier island cross sections can often be schematised using a triangular shape (see Fig. 2). In the case of a dune the seaward and shoreward slopes are steeper than for a barrier island. Waves impacting the seaward side of the beach will cause erosion and a certain portion of the eroded volume (ΔV_o) will be transported across the crest with the overwash (q_B), whereas the rest is transported offshore (q_o). Figure 2 illustrates a triangular beach cross section subject to erosion from wave impact and overwash during a time step, Δt (variables studied change a quantity Δ during this short period). The washover volume (ΔV_B) is assumed to be deposited on the shoreward side maintaining the slope (β_B), and constant slope is also maintained during erosion on the seaward side (β_o). The seaward and shoreward locations of the beach foot are denoted as x_o and x_B, respectively, whereas the beach crest height is s. These three variables uniquely specify the profile change taking place because of erosion and overwash.

The analytical solution to these equations under the assumption of constant values of q_B and q_o is given by,

$$s = \frac{2V_{Do}}{l_{Do}}\sqrt{1-\frac{q_o t}{V_{Do}}} \tag{4}$$

$$x_o = x_{oo} + l_{Do}\left(1+\frac{q_B}{q_o}\right)\left(1-\sqrt{1-\frac{q_o t}{V_{Do}}}\right) \tag{5}$$

$$x_B = x_{Bo} + l_{Do}\frac{q_B}{q_o}\left(1-\sqrt{1-\frac{q_o t}{V_{Do}}}\right) \tag{6}$$

where V_D is the barrier (dune) volume ($V_D = (x_B - x_o)s/2$), l_D the barrier (dune) width ($l_D = x_B - x_o$), and the second subscript *o* denotes the value at *t*=0. The barrier (dune) volume decreases linearly with time because of the offshore losses according to

$V_D = V_{Do} - q_o t$. The overwash volume during a specific event (V_{over}) is defined by the material that is transported over the crest,

$$V_{over} = V_D - \frac{1}{2}\left(x_{Bo} - x_o\right)\left(x_c - x_o\right)\tan\beta_o \tag{7}$$

where:

$$x_c = \frac{x_o \tan\beta_o + x_{Bo}\tan\beta_B}{\tan\beta_o + \tan\beta_B} \tag{8}$$

If $x_o > x_{Bo}$, that is, the front face of the dune or barrier moves past its initial shoreward limit, the overwash volume is given by $V_{over} = V_D$.

3. Data employed

3.1 Storm impact database

Tinh (2006) performed numerical modeling of coastal overwash using an extensive high-quality database of severe storms impacting the United States east coast. Ten events where overwash occurred were identified and detailed data on waves, water levels, and profiles were compiled. The database covered five different storms and 1-4 sites for each storm, including both dune features and barrier islands. Table 1 summarises the hydrodynamic data measured and estimated for the storms, whereas Table 2 yields measured dune and overwash volumes based on the profile surveys.

The Folly Beach data was obtained during hurricane Hugo (Eiser *et al.* 1991) and beach profiles surveyed at four locations were employed. Garden City Beach was also hit by Hugo and profile surveys from one location were available (Eiser *et al.* 1991). Data from Santa Rosa Island were compiled for two hurricanes, namely Opal and George (Stone *et al.* 2004), and from one location. Finally, two major winter storms attacked Assateague Island during January and February 1998, and profile surveys performed at three sites before and after the two storms were available (Larson *et al.* 2004). The runup heights given in Table 1 were computed with the formula developed by Larson *et al.* (2004) in conjunction with the wave impact erosion model.

3.2 Long-term data sets

A long-term data set on hydrodynamics was used to simulate the statistical properties of the morphological response in connection with storms. The data set originated from Ocean City (MD) on the United States east coast. In the simulations schematised subaerial beach cross sections were used based on profile surveys.

Grosskopf (2006) derived this unique, detailed data set on the nearshore hydrodynamics off the coast of Ocean City (MD) based on measurements and numerical modelling. Hourly values on waves, water levels, and wind were available from January 1930 to December 1999. The primary input variables used in the simulations were root-mean-square wave height, peak spectral wave period, storm surge level, and tidal elevation. The hydrodynamic time series included several major storms that occurred along the United States east coast including the September 1933 storm that opened Ocean City inlet, the Ash Wednesday storm March 1962, and the

Halloween storm October 1991. North of Ocean City inlet prominent dunes are present with a height of about 2 m above the dune foot, which is located at an elevation of approximately 3 m above mean sea level. The dunes are partly man-made, constructed and maintained during major beach nourishment operations that started in the end of the 1980's (Stauble *et al.*, 1993). In contrast, south of the inlet a low-lying barrier island is present with a crest height of about 3 m above mean sea level.

4. Validation of analytical model

The data from Tinh (2006) were used to investigate erosion due to wave impact when overwash occurs as well as the relationship between offshore and overwash transport. These quantities are important to specify when applying the analytical solution of dune/barrier island evolution (Eqs. 4-6). Ideally, frequent measurements of the subaerial beach profile would be available during a storm to validate the solution and to determine various coefficient and parameter values. However, even in the most detailed data sets from the field, typically only the pre- and post-storm profiles are obtainable. Thus, the validation has to be made based on recorded volume changes, such as the eroded volume and the overwash volume. The eroded volume from the seaward side of the beach was assumed to be the sum of the measured overwash volume and the overall reduction in beach volume, which is assumed to correspond to the volume lost offshore. This simple picture neglects any complex depositional patterns that may occur during a storm, but at the peak of the storm when large waves attack the beach crest area under elevated storm surge, the estimate should give the correct order of magnitude.

During overwash a portion of the uprushing wave will pass over the crest and the impact from the waves might thus be reduced compared to the case when the entire wave is stopped on the seaward side of the beach (studied by Larson *et al.*, 2004). Thus, a correction factor given by the ratio between the beach crest height and the runup height above the beach foot elevation ($s/(R-z_o)$) was introduced to take this into account. This ratio will only be applied if $R - z_o > s$, that is, if the waves overtop the crest. For overwash conditions, the erosion due to wave impact is expressed as (compare Eq. 2):

$$\frac{dV}{dt} = -4C_s \frac{\left(R - z_o\right)^2}{T} \frac{s}{R - z_o} = -4C_s \frac{\left(R - z_o\right)s}{T} \tag{9}$$

In the evalution of the field data (see Tables 1 and 2), hydrodynamic conditions at the peak of the storm *(i.e.,* maximum wave height and storm surge) were employed as characteristic values. These conditions should be the most important for shaping the profile during overwash, although the forcing is overestimated through this selection of representative conditions. A more sophisticated approach would take into account the detailed time series of the waves and water level, but under such conditions feedback from the morphology should also be included requiring a numerical solution which is outside the scope of the present study. Average transport rates for the storm events were obtained by dividing volume changes with the surge duration, where the latter was taken to represent the event duration. This also provided a coarse description of the actual transport rates during the event that are expected to vary

significantly in time; however, the available data limited the resolution of the processes, as previously pointed out.

Figure 3 shows the observed eroded volume during the events summarised in Tables 1 and 2 as a function of the modified impact parameter. A linear fit to the data is also included following Eq. 9 (because of the logarithmic scale the line appears curved). The best fit line corresponds to a C_s-value of about $4 \cdot 10^{-4}$, which is in agreement with Larson *et al*. (2004), although somewhat higher than what was obtained for the field data. Thus, considering the uncertainties in the analysis, Fig. 3 indicates that the simple correction introduced to take into account the effect of the overwash on erosion from wave impact produces satisfactory results. A more complex relationship between the transport due to wave impact and the impact parameter and/or the correction factor would possibly yield a better agreement between the theoretical curve and the data. At present, due to the limited data employed for validation, a linear relationship was deemed to yield sufficiently good agreement for the purposes here. In Fig. 3 the water level was assumed to reach the front face of the beach during the peak of the storm, implying that $z_o = 0$.

The average offshore (q_o) and overwash (q_B) transport rates were calculated based on the observed volume changes, as previously described. The ratio q_o/q_B should vary during a storm event depending on the relationship between the beach crest height and the runup height (s/R). However, as a first approach, the average values on the transport rates were used for each event (Tables 1 and 2) to plot q_o/q_B versus s/R. Figure 4 illustrates the result for the ten events together with a best-fit straight line. Although the scatter is significant due to the schematization, there is a clear trend of decreasing importance of overwash as s/R increases. As the ratio s/R approaches 1, q_o/q_B should approach infinity as the overwash transport becomes zero (no overtopping due to runup occurs). Thus, the linear fit has its limitations and a more general empirical equation would be,

$$\frac{q_o}{q_B} = A\frac{s/R}{1-s/R} \qquad (10)$$

where A is an empirical coefficient. Figure 4 also shows the nonlinear fit according to Eq. 10 with A=3.0.

5. Simulation of long-term impact of storms

5.1 Technique for assessing probability of storm impact

Storm impact on dunes and barrier islands may be characterised in terms of key morphological parameters such as eroded volume, overwash volume, duration of overwash, and recession distance. A typical method to estimate the probability of a certain impact is to calculate the morphological change caused by a storm event with a certain return period and assign the same return period to that change. However, since a complex combination of different forcing is responsible for the impact, there is not a one-to-one correspondence between the return period of a storm and its effects. Morphological change is primarily caused by a combination of wave height and period (determining the runup height), storm surge height and duration, tidal elevation, pre-storm profile shape, and sedimentological properties. The most appropriate method to derive return periods for various types of storm impact is to

simulate long time series of morphological parameters based on existing time series of hydrodynamic data, and then to perform statistical analysis on the derived data. Such simulations may require simplified models to cover long time periods or to explore many different alternatives when design options are evaluated. In this context analytical solutions are useful to employ for simulating long time series of morphological parameters.

5.2 Case study Ocean City

The analytical solution developed for triangular-shaped dunes and barrier islands (Eqs. 4-6) was employed to estimate eroded volume and overwash volume for two schematised profile shapes, namely a high dune and a low-crested barrier island. The idealised profile shapes were constructed based on the high dunes common north of Ocean City inlet and the low-lying barrier island south of the inlet (Assateague Island) (Stauble *et al.*, 1993). The dune was made 2 m high with a dune foot elevation of 3 m above mean sea level (MSL), whereas the barrier island had a crest elevation of 2 m and the foot of the front-face of the island 1 m above MSL. The equilibrium volume of the dune was set to 80 m^3/m and of the barrier island of 200 m^3/m. Equation 9 was employed in the analytical solution to calculate the sediment transport from the seaward side of the dune or barrier and Eq. 10 to obtain the ratio between the offshore and overwash transport.

The analytical solutions were used to compute the eroded volume and overwash volume during specific events. An event was defined as the time period during which the dune (or barrier island) was continuously exposed to wave impact. The eroded volume for an event was calculated as the sum of the eroded volume at each time step during the event, and the associated duration of the event was recorded. Similarly, the overwash volume and the duration of the overwash were determined when water was transported over the beach crest. It was assumed that the dune and barrier island recovered completely between the events, implying that the storms would always impact the beach at initial conditions, which were taken to represent equilibrium conditions. In order to simulate the effects of storm chronology the recovery process between storms have to be described, for example, dune build-up by wind. Such algorithms have been developed (Larson *et al.*, 2006) but they were not implemented in the present simulations. A representative value of $C_s = 1.7 \cdot 10^{-4}$ was employed on the transport rate coefficient when calculating beach erosion due to wave impact with the analytical model based on Larson *et al*. (2004).

Figures 5 and 6 display the empirical distribution functions for the eroded volume during an event and for the event duration, respectively, for the high dune case (the probability of non-exceedance is shown for different events; the plotting position formula by Weibull was used to obtain the empirical distribution function). Approximately 1500 dune erosion events were calculated for the studied 70-year period, which implies about 20 events/year. The resolution of the event duration is 1 hr, which gives the distribution function for the duration a “jagged” shape at short return periods. The shape of the distribution function in Fig. 5 is complex, possibly indicating that different types of processes are responsible for the eroded volume associated with different return periods. For example, it is expected that extreme storms on the United States east coast, such as hurricanes or northeasters, would have a different type of impact than more “normal” storms.

Figures 7, 8, and 9 illustrate the distribution functions for eroded volume, overwash volume, and overwash duration, respectively, for the barrier island case. Because of the low elevation of the foot of the front face the island is frequently exposed to wave attack and on the average erosion events would occur almost 1.5 times/day. The low crest implies that overwash takes place more than 10 times/year. As seen for the dune case the distribution functions exhibit complex shapes indicating processes of different origin affecting the barrier island erosion and overwash.

The necessity of taking into account the combined effects of waves and water levels when assigning the probability of a specific impact is clearly illustrated by analyzing the largest overwash events calculated for the high dune case. For the study period, the largest overwash event recorded was for the Ash Wednesday storm in March 1962 (V_{over}=33 m^3/m), followed by storms in December 1992 (V_{over}=30 m^3/m), September 1933 (V_{over}=29 m^3/m), and November 1981 (V_{over}= 21 m^3/m). As a comparison, the maximum measured hydrodynamic parameters occurred according to: maximum wave height H_{rms}=4.4 m in January 1938, and maximum water level 2.1 m in September 1960. Both these extreme hydrodynamic events yielded minor overwash volumes, not among the 10 largest events recorded. Thus, assigning probabilities to specific morphological impact events based on analysis of individual forcing parameters will not be sufficient in many situations.

II: SIGNIFICANT ADMINISTRATIVE ACTIONS AND OTHER INFORMATION

No significant administrative actions were taken.

III: FUNDS REMAINING AND LIST OF PROPERTY ACQUIRED

The total contract is for $570,000. Payment upon receipt of these reports is scheduled at $50,000. Therefore, the amount of funds remaining under contract at the end of this report period is $420,000.

REFERENCES

Cross, R.H. 1967. Tsunami surge forces. *Journal of the Waterways and Harbors Division*, Vol. 93, No. 4, 201-231.

Donnelly, C., Kraus, N.C., and Larson, M. 2006. State of knowledge on measurements and modelling of coastal overwash. *Journal of Coastal Research*, Vol. 22, No. 4, 965-999.

Donnelly, C., Larson, M., and Hanson, H. 2007. A numerical model of coastal overwash. *Maritime Engineering*, ICE, Proceedings of the Institution of Civil Engineers, (in review).

Eiser, W.C. and Birkemeier, M. 1991. Beach profile response to Hurricane Hugo. *Proceedings Coastal Sediments'91*, ASCE, 1681-1696.

Erikson, L., Larson, M., Hanson, H., Kraus, N.C., and Nishi, R. 2003. Prediction of notching and mass failure of dunes. *Proceedings of Coastal Sediments '03*, ASCE (on CD).

Erikson, L., Larson, M., and Hanson, H. 2007. Laboratory investigation of dune recession due to notching and subsequent failure. *Marine Geology*, 245, 1-19.

Fisher, J.S. and Stauble, D.K. 1977. Impact of Hurricane Belle on Assateague Island washover. *Geology*, 1977, Vol. 5, 765-768.

Fisher, J.S., Overton, M.F., and Chisholm, T. 1986. Field measurements of dune erosion. *Proceedings of the 20th Coastal Engineering Conference*, ASCE, 1107-1115.

Grosskopf, W.G. Data transfer, 2006.

Hughes, M.G. 1992. Application of a non-linear shallow water theory to swash following bore collapse on a sandy beach. *Journal of Coastal Research*, Vol. 8, No. 3, 562-577.

Kobayashi, N., Tega, Y., and Hancock, M.W. 1996. Wave reflection and overwash of dunes. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, Vol. 122, No. 3, 150-153.

Kraus, N.C. and Wise, R.A. 1993. Simulation of January 4, 1992 storm erosion at Ocean City, Maryland. *Shore and Beach*, Vol. 61, No. 1, 34-41.

Kriebel, D.L and Dean, R.G. 1985. Numerical simulation of time-dependent beach and dune erosion. *Coastal Engineering*, Vol. 9, 221-245.

Larson, M. and Kraus, N.C. 1989. SBEACH: Numerical model for simulating storm-induced beach change. Report 1: Empirical foundation and model development. Technical Report CERC-89-9, Coastal Engineering Research Center, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Larson, M., Wise, R.A., and Kraus, N.C. 2004a. Modeling dune response due to overwash transport. *Proceedings 29th Coastal Engineering Conference*, World Scientific Press, 2133-2145.

Larson, M., Erikson, L., and Hanson, H. 2004b. An analytical model to predict dune erosion due to wave impact. *Coastal Engineering*, Vol 59, No. 8/9, 675-696.

Larson, M., Kraus, N.C., and Connell, K. 2006. Modeling sediment storage and transfer for simulating regional coastal evolution. *Proceedings of the 30th Coastal Engineering Conference*, World Scientific, 3924-3936.

Leatherman, S.P. 1979. Barrier dune systems: A reassessment. *Sedimentary Geology*, Vol. 24, 1-16.

Miller, R.L. 1968. Experimental determination of run-up of undular bores and fully developed bores. *Journal of Geophysical Research*, Vol. 73, No. 14, 4497-4510.

Nishi, R. and Kraus, N.C. 1996. Mechanism and calculation of sand dune erosion by storms. *Proceedings of the 25th Coastal Engineering Conference*, ASCE 3034-3047.

Overton, M.F., Fisher, J.S., and Fenaish, T. 1987. Numerical analysis of swash forces on dunes. *Proceedings of Coastal Sediments '87*, ASCE, 632-641.

Stauble, D.K., Garcia, A.W., Kraus, N.C., Grosskopf, W.G., and Bass, G.P. 1993. Beach nourishment project response and design evaluation: Ocean City, Maryland. Report I. 1988-1992. Technical Report CERC-93-13, USAE Waterways Experiment Station, Vicksburg, MS.

Steetzel, H.J. 1993. Cross-shore transport during storm surges. Ph.D. thesis, Technical University Delft, CASPARIE Publishers, Zwolle.

Stone, G.W., Liu, B., Pepper, D.A, and Wang, P. 2004. Importance of extratropical and tropical cyclones on the short-term evolution of barrier islands along the northern Gulf of Mexico, USA", *International Journal of Marine Geology, Geochemistry and Geophysics,* 63-78.

Tinh, N.X. 2006. Modelling of coastal overwash. Report TVRL 2006:1, Department of Water Resources Engineering, Lund University, Lund.

Waddell, E. A. 1973. field investigation of swash characteristics. *Coastal Engineering in Japan*, Vol. 16, 61-71.

Table 1. Hydrodynamic conditions during studied storms (H_{rms}: root-mean-square wave height; T_o: peak spectral wave period; ΔR: runup height above beach crest; and d_{50}: median grain size) (after Tinh, 2006)

Profile	H_{rms} (m)	T_0 (s)	Water depth (m)	Max. water level (m)	Runup above SWL (m)	Crest above SWL (m)	Max. ΔR (m)	Surge duration (hrs)
Folly Beach 2801	4.78	10.79	16	2.13	4.65	2.02	2.51	8
Folly Beach 2815	4.78	10.79	16	2.13	4.65	2.23	2.30	8
Folly Beach 2823	4.78	10.79	16	2.13	4.65	2.02	2.51	8
Folly Beach 2883B	4.78	10.79	16	2.13	4.65	2.05	2.48	8
Garden City 4930	5.04	10.95	16	2.42	4.85	2.28	2.57	10
Santa Rosa Island, Opal	5.84	11.22	27	2.57	5.35	2.24	3.11	13
Santa Rosa Island, Georges	5.89	11.92	20	1.38	5.71	0.74	4.97	77
Assateague Island, GPS1	2.90	16	15	1.91	5.38	0.39	4.99	283
Assateague Island, GPS3	2.90	16	15	1.91	5.38	0.14	5.24	357
Assateague Island, GPS4	2.90	16	15	1.91	5.38	1.69	3.69	69

Table 2. Dune volume before and after storm and overwash volume (after Tinh, 2006)

Profile name	Change in Dune/Barrier volume (m^3/m)	Overwash Volume (m^3/m)	d_{50} (mm)
Folly Beach 2801	-0.78	4.75	0.17
Folly Beach 2815	-18.37	11.89	0.17
Folly Beach 2823	-16.09	5.58	0.17
Folly Beach 2883B	-12.61	4.19	0.17
Garden City 4930	-30.47	17.58	0.44
Santa Rosa Island, Opal	-160.1	55.7	0.26
Santa Rosa Island, Georges	-11.2	57.13	0.26
Assateague Island, GPS1	-18.9	50.1	0.3
Assateague Island, GPS3	19.5	101.4	0.3
Assateague Island, GPS4	-74.6	91.5	0.3

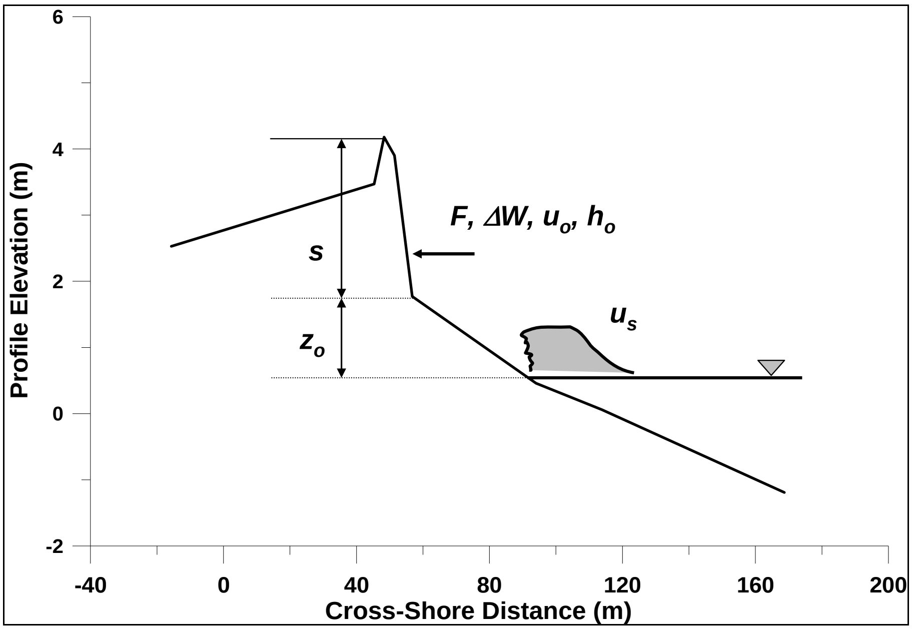

Figure 1. Definition sketch for analytical model of dune erosion.

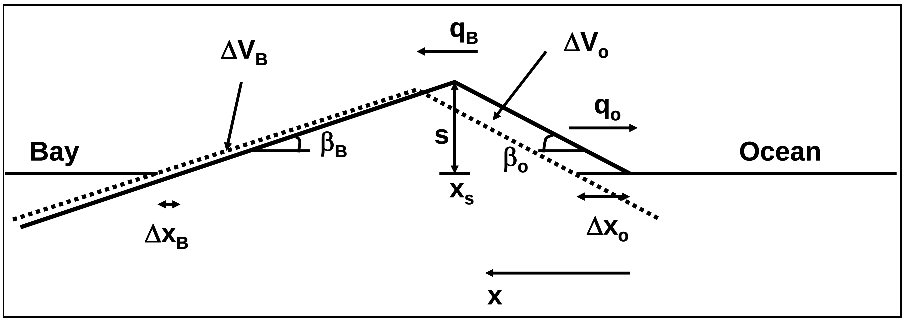

Figure 2. Schematic of a beach cross section subject to wave impact and overwash.

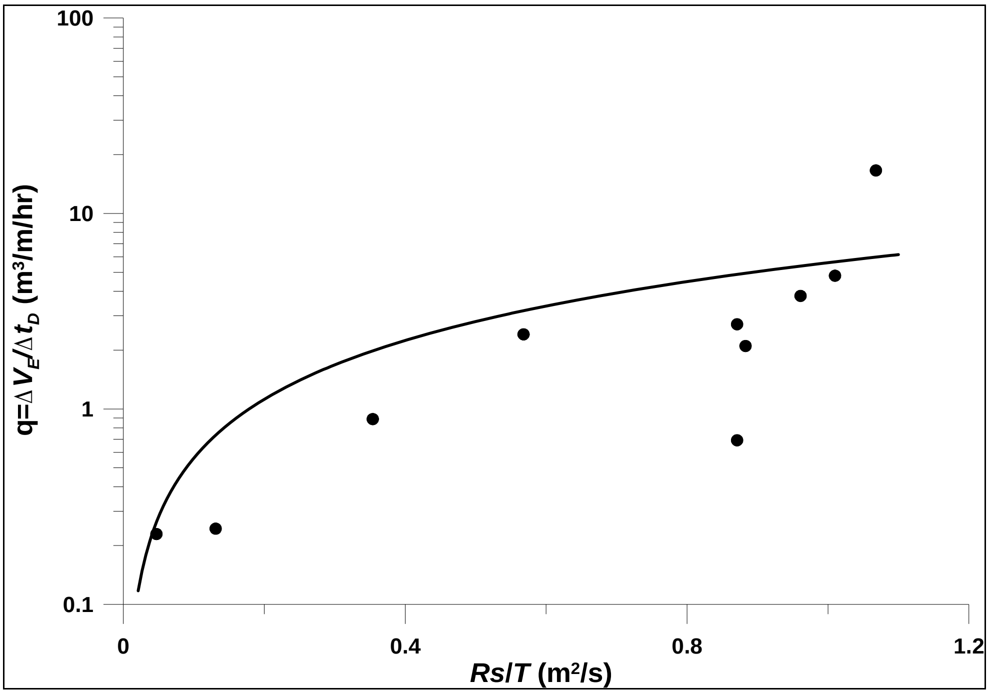

Figure 3. Eroded volume during a storm event (*i.e.*, mean transport rate) as a function of an impact parameter modified with respect to the relative ratio between beach crest height and runup height.

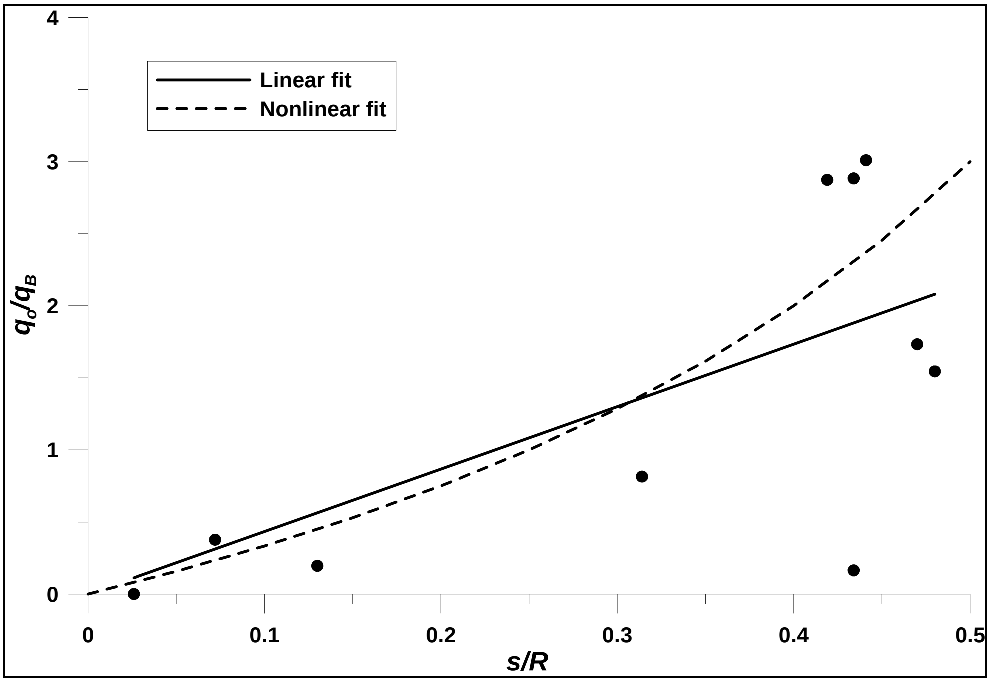

Figure 4. Ratio between average offshore (q_o) and overwash (q_B) transport as a function of relative ratio between beach crest height and runup height.

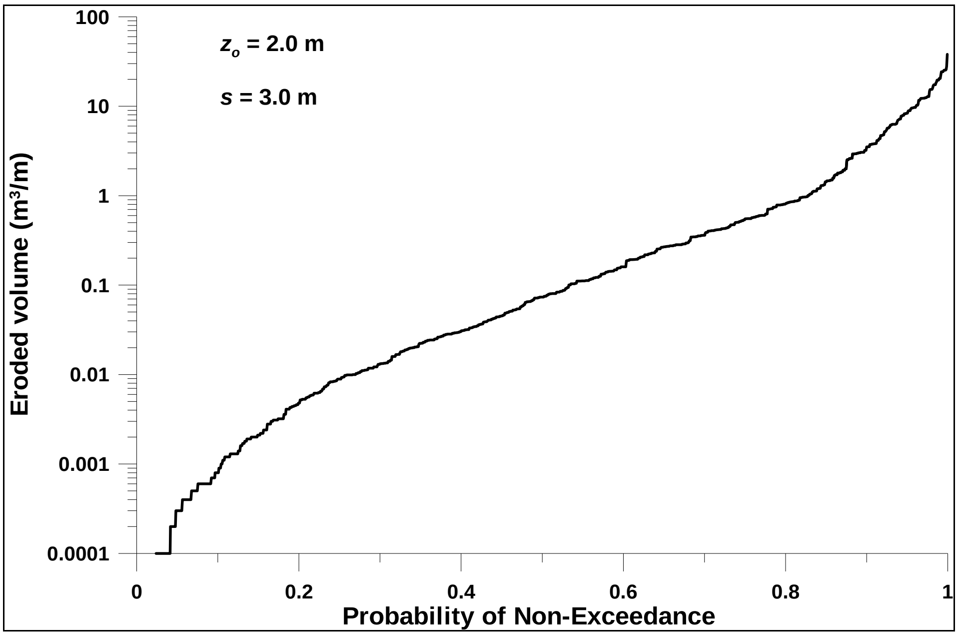

Figure 5. Empirical distribution function describing the probability of non-exceedance for a specific eroded volume during a storm event attacking a high dune at Ocean City, Maryland.

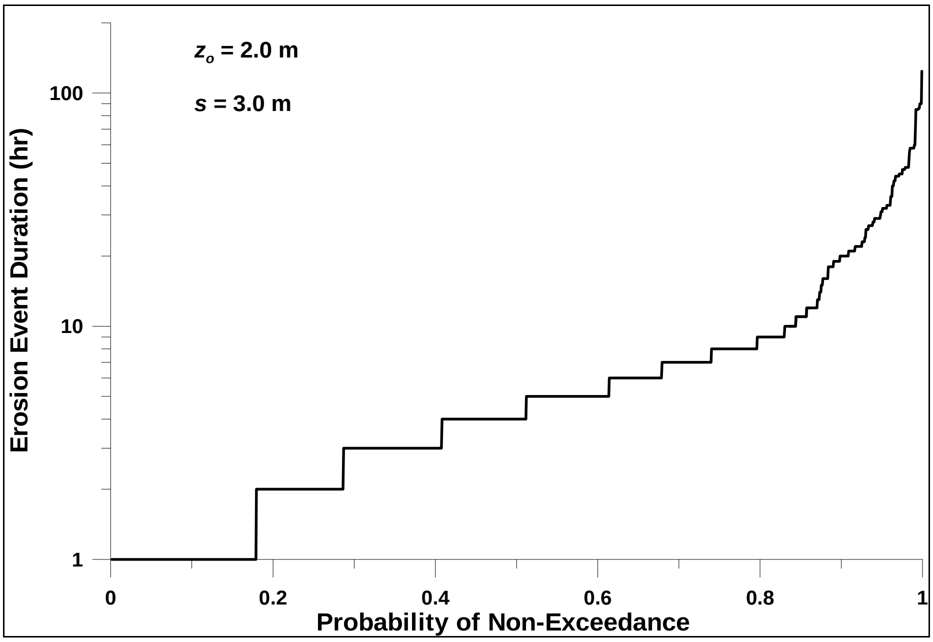

Figure 6. Empirical distribution function describing the probability of non-exceedance for a specific duration of dune erosion for a storm event attacking a high dune at Ocean City, Maryland.

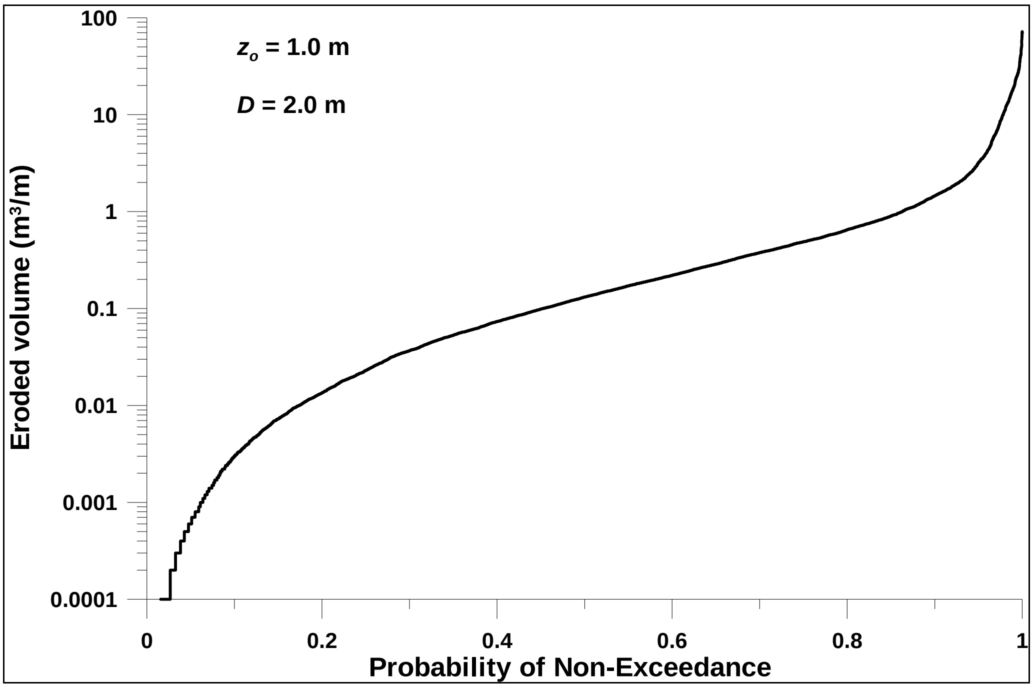

Figure 7. Empirical distribution function describing the probability of non-exceedance for a specific eroded volume during a storm event attacking a barrier profile at Assateague Island, Maryland.

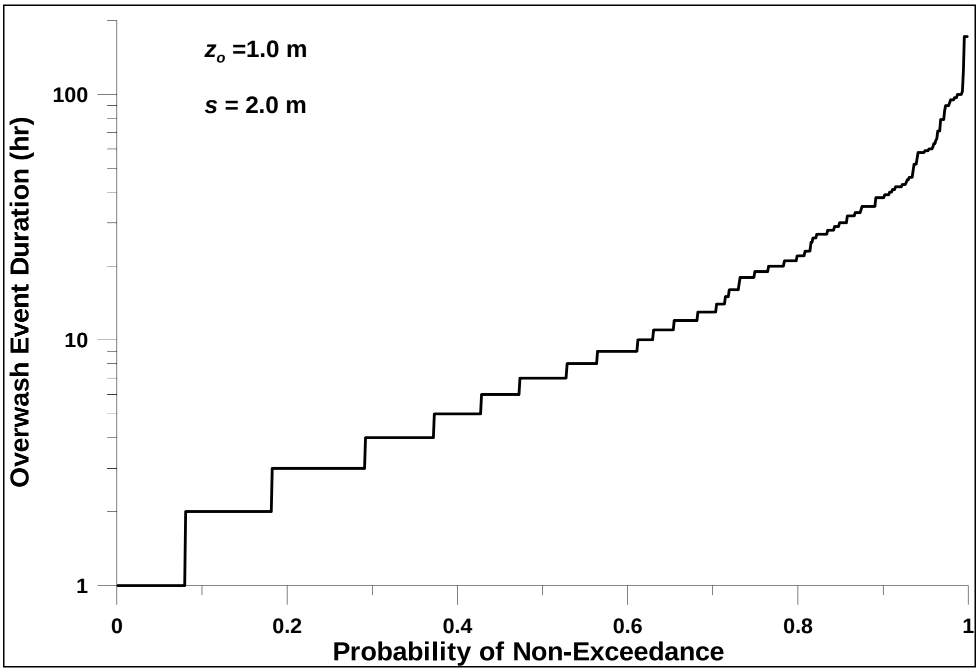

Figure 8. Empirical distribution function describing the probability of non-exceedance for a specific overwash duration during a storm event attacking a barrier profile at Assateague Island, Maryland.

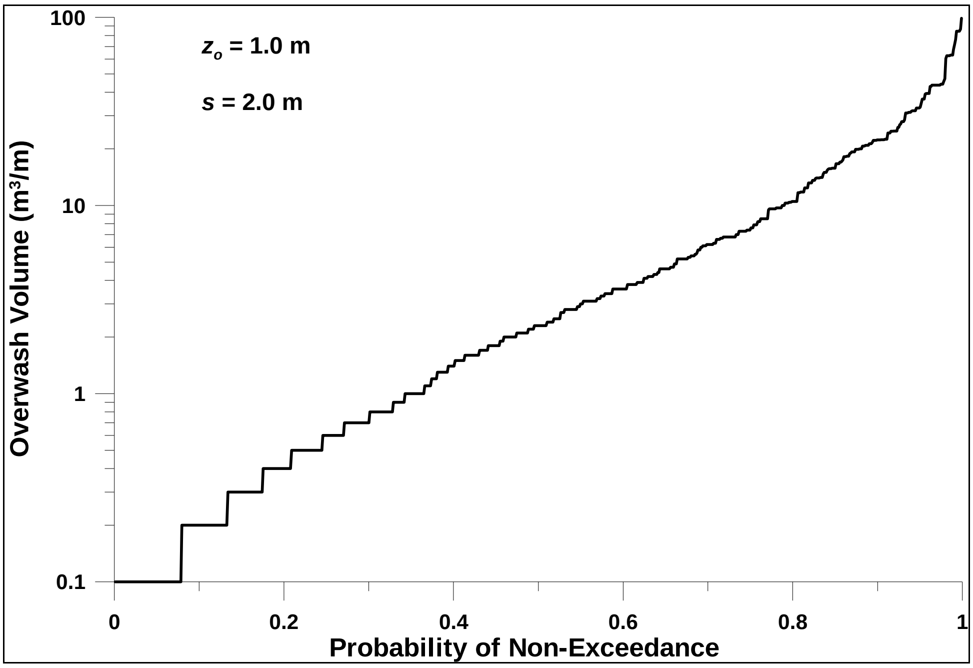

Figure 9. Empirical distribution function describing the probability of non-exceedance for a specific overwash volume during a storm event attacking a barrier profile at Assateague Island, Maryland.